

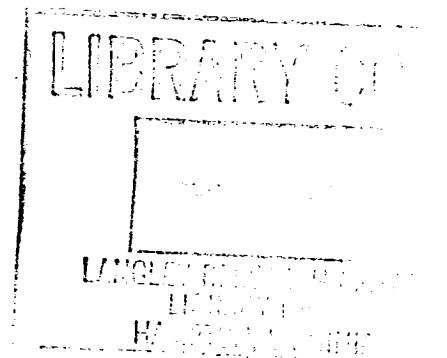
NASA Technical Memorandum 105192

Technical Evaluation Report, AGARD  
Fluid Dynamics Panel Symposium  
on Effects of Adverse Weather  
on Aerodynamics

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October 1991

**NASA**





## TECHNICAL EVALUATION REPORT

AGARD Fluid Dynamics Panel Symposium on  
Effects of Adverse Weather on Aerodynamics

by

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### SUMMARY

The Fluid Dynamics Panel of AGARD sponsored a Specialists Meeting on "Effects of Adverse Weather on Aerodynamics" on April 29 to May 1, 1991, in Toulouse, France. The purpose of the meeting was to provide an update of the state-of-the art with respect to the prediction, simulation and measurement of the effects of icing, anti-icing fluids and various forms of precipitation on the aerodynamic characteristics of flight vehicles. Sessions were devoted to introductory and survey papers and icing certification issues, to analytical and experimental simulation of ice frost contamination and its effects on aerodynamics, and to the effects of heavy rain and deicing/anti-icing fluids. The 19 papers announced for the meeting are published in AGARD Conference Proceedings CP-496 and are listed in the Appendix of this report. A brief synopsis of each paper and some discussion, conclusions and recommendations are given in this evaluation report.

### INTRODUCTION

The 68th Meeting of the AGARD Fluid Dynamics Panel Specialists Meeting was held on April 29 to May 1, 1991, in Toulouse, France. Its theme, as published in the AGARD announcement, was the following:

In recent years, a number of weather-related accidents, along with the introduction of new types of anti-icing fluids and apparent uncertainties in certification and operation procedures, have stimulated renewed research activities. Aircraft operators, the aircraft industry, as well as research institutes and certification authorities, are participating in such activities.

The purpose of the Specialists' Meeting is to provide an update of the state-of-the-art with respect to the prediction, simulation and measurement of the effects of icing, anti-icing fluids and various forms of precipitation on the aerodynamic characteristics of flight vehicles and to communicate research results on these topics that have been obtained in recent years.

The 2-1/2 day meeting was divided into three sessions:

- Session I. Icing 1—Introductory and Survey Papers, Certification Issues
- Session II. Icing 2—Prediction and Simulation of Ice Contamination and its Effects
- Session III. Effects of Heavy Rain and De/Anti-Icing Fluids

The meeting agenda listed 19 papers, and all except two (numbers 2 and 12) were presented at the meeting. Fortunately, the written version of paper 2 was available at the meeting, and paper 12 was later received by the

technical evaluator. Written versions of papers 10 and 18 were not available at the meeting, but drafts of the papers were later received by the technical evaluator. The 19 papers were published in AGARD Conference Proceedings CP-496. The titles of the 19 contributions are listed in Appendix A. The members of the Program Committee for the meeting are given in Appendix B.

The meeting's potential scope was far reaching, encompassing at least the following areas: all aircraft classes; effects of adverse weather on component performance and on aircraft performance and stability; a wide range of rain, icing, and winter weather conditions that produce an infinite continuum of types and amounts of surface roughness; both wind tunnel and flight testing research; and state-of-the-art computer code development. Considering this broad scope, it is to the Meeting Committee's credit that their selection of papers gave a balanced overview of the state-of-the-art with respect to prediction, simulation, and measurement of the effects of icing, anti-icing fluids, and precipitation (snow, frost, and heavy rain) on the aerodynamic characteristics of flight vehicles.

Three papers were devoted to various aspects of icing certification. One paper reviewed the FAR/JAR 25 regulations and the proposed French supplement Joint Advisory Material AMJ 25-1419. This AMJ defines standardize flight test procedures for demonstrating that an airplane's performance and handling qualities are acceptable when lifting surfaces are contaminated with ice that accumulates in flight. Two other papers gave examples of computer calculations for droplet trajectories, and one of these reviewed the airframe and engine testing done in support of certification. Two papers reviewed previous AGARD meetings that contained extensive material relevant to the present meeting's objectives. Another paper gave an overview of the analytical and experimental simulation methods currently employed in icing research and technology. One paper reviewed the major codes used in an ice accretion prediction program and gave comparisons between predicted and measured ice shapes.

Three papers presented experimental data for the effects of surface roughness on boundary layer development or on lift and drag versus angle of attack. One of these papers measured the boundary layer growth for flow over a flat plate covered with simulated frost. The frost was replicated by a little-known technique in which the actual frost was covered with a dissolved liquid plastic. The frost data were used to modify a boundary layer analysis and to predict the effects of surface roughness on wing aeroperformance and on takeoff performance. Another paper in this group included propeller power effects in a wind tunnel study of the effects of sand grain roughness on airfoil performance. The third paper presented wind tunnel data for a sub-scale model aircraft with simulated hoar-frost on the wings and used the data in a groundbased

engineering simulator to investigate the degradation in performance and handling qualities during take-off. This is one of only a few published studies in which a simulator was used to investigate the effects of wing contamination on flight characteristics.

Two papers presented the effects of surface roughness on high lift airfoils. One of these papers provided correlations for three essential flight characteristics: percent loss in maximum lift, percent increase in stall speed, and reduction in stall angle of attack. The data covered several orders of magnitude of roughness height-to-chord ratio. And data was presented for both retracted and extended leading edge devices. The other paper showed recent wind tunnel data on the sensitivity of airfoils to sand roughness and presented percent loss in maximum lift versus wing chord Reynolds number for three roughness height-to-chord ratios. This important new data on Reynolds number effects has long been sought by those concerned with surface roughness and by the aircraft icing community which is considering deicing systems as a possible alternative to thermal anti-icing systems.

One paper presented dry-air wind tunnel measurements and corresponding three-dimensional Navier-Stokes code calculations for the flow field around semi-span, straight and swept wings with artificial leading edge ice shapes. This research effort shows the valuable advantages of concurrently conducting both computer code development and supporting code validation experiments.

Two papers were devoted to ground deicing/anti-icing fluids. One paper presented flight and wind tunnel test results on the effects of these fluids on takeoff performance, established allowable losses in maximum lift for jet transports, and evolved criteria for aerodynamic acceptance tests of such fluids for jet transports. A second paper, in collaboration with the first paper, presented a simplified wind tunnel test to determine if a fluid passed the aerodynamic acceptance criteria. The acceptance test involved measuring the boundary layer thickness at the trailing edge of a flat plate covered with the fluid.

Two papers addressed helicopter rotor icing. Both presented comparisons of computer code predictions against flight and/or wind tunnel data for rotor performance in icing. One also presented results of a model rotor test in an icing wind tunnel and assessed the merits of sub-scale rotor icing tests.

Three papers were devoted to heavy rain effects. The first presented both sub-scale and full-scale aerodynamic performance test results for two-dimensional multi-element airfoils, and it also included measured heavy rainfall rates at selected sites around the world. The second paper also presented wind tunnel test results on another sub-scale two-dimensional high lift airfoil model. The third paper presented results for the measurement of liquid water films using conductance sensors.

Although the measurement and prediction of boundary layer development on rough surfaces has an extensive bibliography (Refs. 1 to 4), there has been only limited progress toward developing accurate analytical predictions (Refs. 5 and 6). And although the aerodynamics of rough airfoils is at the cutting edge of computational fluid dynamics, it has received only limited attention. Today's

analytical approaches depend heavily on empirical correlations because of the current lack of appropriate turbulence models and/or discrete roughness models, and because it is difficult to accurately calculate Navier-Stokes flows or boundary layer flows beyond stall. Furthermore, there exists no systematic body of experimental data for flows over single and multi-element airfoils with appropriate roughness simulation and coverage and Reynolds number range. Thus, those in the field of surface roughness aerodynamics must either work with highly empirical analytical models or pioneer new aerodynamic flow models. And because of practical constraints, they must limit fundamental wind tunnel and flight test studies to only a few airfoil configurations and to only a small subset of the known surface roughnesses that nature can produce. Some of these limited, but very important studies, were presented in this meeting.

## SUMMARY OF AND COMMENTS ON THE PAPERS

In summarizing these papers, the author of this present technical evaluation, rather than trying to paraphrase already good prose, freely excerpted segments from the papers without using the usual attributory quotation marks. This was done to minimize clutter in the text. Occasionally quotation marks were used. In the final analysis, these summaries reflect the evaluator's interpretations and prejudices, and in no way should be attributed to the authors of the original papers.

### Icing 1—Introductory and Survey Papers, Certification Issues

Paper 1 - RANAUDIE gave a report on the AGARD Flight Mechanics Panel Symposium entitled "Flight In Adverse Environmental Conditions," held in Gol, Norway, May 1989. The 26 papers from this symposium were published in AGARD-CP-470. Mr. RANAUDIE concentrated on selected papers from each of the five sessions: (1) Atmospheric Measurements and Modelling; (2) Effect of Disturbances on Design and Operations; (3) Visibility; (4) Icing; and (5) Electromagnetic Disturbances. The two major types of severe atmosphere disturbances were high-altitude turbulence (due to thunderstorm fronts or mountain ranges, both of which were accompanied by temperature inversions) and low-level microbursts. Fixed simulator approaches in microburst wind shear conditions demonstrated the important and dramatic advantages of pilot training. The recommended crew procedures during low-level windshear are (1) avoid if you can, (2) pull up, attitude 15°, and (3) forget all previous experience. The flight controls for the Airbus A320 were described as having (1) stall warning—only aircraft that can fly near maximum lift, (2) auto triggering of full thrust at high alpha or when pilot pulls pitch control, and (3) future plans for windshear warning and automatic reaction system. In the session on electromagnetic interferences, it was noted that lightning occurred at the unexpected conditions of -40 °C ambient temperature, where the relative turbulence and precipitation intensities were characterized as negligible to light. Most aircraft lightning strikes were triggered by the vehicle itself, i.e., short-circuiting between clouds of opposite polarity. RANAUDIE also reviewed the comprehensive report presented on NASA's icing technology program.

Paper 2. - BRUMBY was unable to attend the meeting, but copies of his paper were available at the meeting. This paper appropriately set the stage for all that followed on the effects of wing ice contamination on flight characteristics. He reviewed the effect of wing ice contamination on three essential flight characteristics: percent increase in stall speed, percent decrease in maximum lift coefficient, and reduction in stall angle. Both characteristics were plotted against  $k/c$  (ratio of roughness height to wing chord). The parameters included roughness over the entire upper surface with slats retracted and with slats fully extended, and roughness on just the leading edge with slats retracted and with slats fully extended. The plot for percent loss in maximum lift coefficient is included as Fig. 1 of this report. His data is taken from wind tunnel and flight test results.

For takeoff with frost, snow, ice, or slush adhering to the wings, the appropriate curve in Fig. 1 would be for roughness over the entire upper surface. For example, moderate frost would have a roughness of about 0.3 mm (0.012 in.), and on a 10-ft chord wing would give a  $k/c$  of about 0.0001, which would lead to about a 15 percent loss in maximum lift. To get down to about a 2 or 3 percent loss in maximum lift requires, according to Fig. 1, less than 0.15 mm (0.006 in.) on a 10-ft chord wing.

Another important point made by BRUMBY was that a reduction in stall angle accompanies the loss in maximum lift, and this can lead to two adverse effects. First, if wing ice causes a stall before the stall warning's prescheduled angle of attack is reached, the flight crew will receive no warning of impending stall. Second, the reduced stall angle compounds the problem of the tendency of an ice-contaminated, swept-wing airplane to pitch up during rotation, increasing the risk of overshooting the stall angle shortly after liftoff.

Thus, it's easy to see why BRUMBY concluded that "From an aerodynamic viewpoint, there is no such thing as 'a little ice.' Strict attention should be focused on ensuring that critical aircraft surfaces are free of ice contamination at the initiation of takeoff."

It might seem that Mr. Brumby's conclusions applied only to swept-wing, jet transports that tend to pitch up if the wing stalls at takeoff. But in his paper he says that "ice contamination is quite democratic, adversely affecting straight-wing aircraft such as the Nord 262 and numerous general aviation aircraft; small turbojet aircraft with conventional airfoils such as the Learjet; larger aircraft with conventional airfoils such as the F-28, DC-9-10, and DC-8; and aircraft with leading edge high-lift devices such as the 737."

The other curves on Fig. 1, designated as roughness on the leading edge only, are sometimes used to estimate the thickness of ice allowed to accumulate during in-flight icing. Some important new data presented in paper 12 indicate that these curves underestimate the aerodynamic penalties caused by ice that forms on the leading edge during flight in supercooled clouds.

Paper 3. - JACQUES gave a report on the AGARD 76th Symposium of the Propulsion and Energetics Panel on "Low Temperature Environment Operations of Turboengines (Design and User's Problems)," held in Brussels, Belgium, October 1990. The 33 papers were

published in AGARD-CPP-480. The turboengine symposium, which addressed the effects of ice on engine performance, nicely complemented the present meeting, which addressed the effects of ice on external aircraft performance. Professor JACQUES noted under Operational Concerns that ice buildup on or within engine inlets can lead to loss of total pressure or flow distortion, which in turn can lead to compressor surge and stall. Ice ingestion can damage fan blades or cause engine flame outs. He showed several solutions to ice buildup on inlet screen and in inlet ducts, with the usual solution being the use of bypass flow systems and inertial particle separators. In one surprising case, in spite of apparently successful tests of the ice protection system in the engine test cell and in natural icing tests, an unacceptable level of foreign object damage caused by ice ingestion was observed in icing flight operations. Several modifications to the ice protection system did not provide sufficient ice FOD resistance, and the only solution was to develop ice FOD-resistant compressor blades.

The symposium contained excellent discussions of engine test facilities and calibration concerns and procedures. The symposium also presented good examples of computer codes used both in icing facility calibrations and in the design of ice protection systems. Computer codes for both water droplet trajectory and ice accretion prediction were discussed.

One paper described how low temperature operations can cause fuel to form solid wax precipitates that can cause plugging of filters or blockage of fuel transfer lines. Another paper showed that water dissolved in the fuel can form ice crystals and block the filters, fuel controllers, and passages in heat exchangers. A computer code was identified that predicts fuel temperatures in fuel tanks.

Paper 4. - CATTANEO gave a talk on current FAA/JAR 25 regulations for certification of civil aircraft for flight into known icing conditions. He presented the French Certification Authority's proposed regulatory changes to FAA/JAR 25 as embodied in Advisory Material Joint AMJ 25-1419. This AMJ is partially based on AMA 525/2-x and 525-5-x of the Canadian DOT. Mr. CATTANEO noted that atmospheric conditions are well defined in Appendix C of FAR/JAR 25 and that methods for testing and analyzing the performance of ice protection systems (IPS) are well defined. But there is no correspondingly well defined set of flight tests for determining the effects of ice accumulations on aircraft performance and handling qualities. Terms for safety are vague. There is confusion about interpretation of tests and about the required amount and proportion of testing in natural icing and in clear air with artificial ice shapes.

He noted that even thin ice (4 mm thickness) can reduce lift by 20 percent and stall angle by 3°, can significantly increase drag, can affect static and dynamic pitch and roll stability, can produce a large loss in elevator efficiency, and can cause an inversion of hinge moments with mechanical flight controls. Special attention should be paid to pushover to reach zero g because there is a loss of 1° to 2° of tail stall angle caused by icing.

Cattaneo proposed that icing flight trials be carried out mostly with artificial ice shapes in clear air testing and be backed up with testing in natural icing conditions to catch the complete aircraft icing problem. The artificial

ice shapes should be computed with ice accretion computer codes that have been experimentally validated. The size of ice depended on whether the part was protected or unprotected, and on various engine and ice protection system failures.

The paper gave the following discussion on size and roughness of the artificial ice.

**Takeoff:** To be performed with an engine failure. Ice is accumulated on the entire set of surfaces for a specified angle of attack and for a specified duration.

**Cruise, hold, and landing:** On unprotected parts of the aircraft, ice formation has a maximum depth of 3 in. with surface roughness of 3 mm and a density of grains of 8 to 10 grains/cm<sup>2</sup>. On protected parts, the time required in activating the systems for deicing and anti-icing, both unavoidable and procedural, are considered, both for ice accumulated between deicing cycles and for any runback and refreezing beyond the deicer heaters.

**IPS failure in flight:** For failures requiring the aircraft to leave the area of icing conditions, the thickness of ice on the protected parts is set at 1.5 cm.

**Special case of sandpaper:** A specific form of ice, that with a small thickness and the abrasiveness of sandpaper, has been used to qualify the behavior of aircraft during push over maneuvers. It is known by experience that this type of accretion may have a large effect on this maneuver.

The paper also described the following tests to be performed during flight.

**Systems performance:** Determination of time to remove ice after actuation of IPS.

**Flight qualities:** Characteristics of ice removal. Roll and yaw stability. Transverse dynamic stability (Dutch roll). Trim capacity. Vibrations and buffeting. Absence of blocking of rudders and aileron (jamming). Roll behavior in pushovers to the limit of the flight envelope:  $n=0$  g VFE.

**Flight in natural icing conditions:** Purpose of these tests is to (1) validate the artificial ice forms for subsequent use, and (2) assure that the degradations of performance and flight handling quality observed with the artificial types of icing were conservative.

**Stall warning/stick shaker settings** should be set for greatest possible range of icing conditions, for ice coating thicknesses of up to 3 cm on the protected parts and 1 cm on the unprotected parts. (Stall warning is further discussed below).

The rest of the paper gives results for the application of the AMJ to the certification of the ATR 72, and as an experimental project, to a Fokker 27 that was designated the Aircraft for Atmospheric Research and Remote Sensing (ARAT).

Cattaneo's experience has been that flight performance losses were more severe with artificial ice shapes than with natural ice shapes. As noted above, AMJ 25-1419 proposed that when the ice protection system is turned on, the stall

warning indicators should be reset to values appropriate to the lower stall angle observed in the icing flight trials. In this regard, this evaluator recently learned that the ATR-42, ATR-72, and the Dash 8-300 automatically shift stall warning to lower angles of attack when the anti-icing is turned on. (Any anti-icing systems on the aircraft are turned on before the deicing systems.) Also, at least in Canada, if an aircraft with conventional pneumatic deicer boots had been in icing just prior to approach, the stall speed must be increased during approach to adjust for a loss in maximum lift caused by the maximum growth of ice (about 12.5 mm thickness for conventional pneumatic boots) on the deicers just prior to actuation. It is also common practice, when an airplane has been in icing conditions just prior to approach, to limit the degrees of flap during approach and landing to prevent tail stall.

The AMJ 25-1419 regulations described above are intended for twin engine aircraft with mechanical flight controls, such as the Fokker 27. The French are considering a similar implementation for aircraft with a larger flight range, e.g., the Dornier 328, Jetstream, A330 and A340.

**Icing 2—Prediction and Simulation of Ice Contamination and its Effects on Aerodynamics**

**Paper 5.** - POTAPCZUK and REINMANN presented a survey of the current methods for simulating the response of an aircraft or aircraft subsystem to an icing encounter. This work covered the entire field of icing simulation and included 81 references. Topics discussed included computer code modeling of droplet trajectories, of aircraft icing, and of aircraft performance degradation in icing. Also covered were experimental icing simulation wind tunnels, engine test cells, in-flight spray tankers, and ground spray test facilities. Special test techniques, such as icing scaling laws and subscale helicopter models in icing tunnels, were discussed. It is generally agreed that icing simulation, where applicable, is more desirable than testing in natural icing because it presents lower risks, costs less, consumes less time, is more reproducible, and it may more readily be included in simulators for certification and pilot training. But flight testing in natural icing will always remain a part of the certification process and will be needed to validate the analytical and experimental simulation methods. The concluding remarks identified several areas requiring further research in icing simulation. These are:

1. Ice accretion physics; specifically, roughness characterization, heat transfer correlations, splashing, runback, surface tension effects, and wetting characteristics.
2. Ice structural properties and ice shedding.
3. Stall mechanisms and post-stall behavior of iced wings. Computational simulation of these phenomena.
3. Inclusion of surface roughness effects in aerodynamics codes.
4. Evaluation of turbulent flow properties for iced wings and development of appropriate turbulence models.
5. Three-dimensional ice accretion code development.

6. Computer code simulation of iced wing and iced aircraft performance. Development of performance codes for rotorcraft in icing.

7. Continued development of computational methods for simulating ice protection systems.

8. Continued development of experimental methods for simulating rotorcraft performance in icing.

9. Creation and verification of icing scaling laws.

Paper 6. - PREL presented an analysis of three-dimensional droplet trajectories about an aircraft. The flow over the aircraft was calculated with a three-dimensional panel code called FP3D that was developed by Aerospatiale. The droplet trajectory calculation procedure was based on a method developed by D. Guffond at ONERA. Code results showed how droplet trajectory predictions could be used to help locate cloud instrumentation on the aircraft so as to insure that measured cloud properties were representative of freestream cloud conditions. Thus, instruments must not be placed in cloud shadow zones, nor should they be placed in regions where droplets are concentrated or dispersed by interaction with the flowfield around the airplane. Not presented were any comparisons between the computer-predicted results and experimental droplet trajectory data.

Paper 7. - POTAPCZUK, BRAGG, KWON, and SANKAR presented the results of a computational and experimental study of the sectional and total aerodynamic load characteristics of moderate aspect ratio, swept and nonswept wings with and without simulated glaze leading edge ice. The computations were done with a three-dimensional, compressible Navier-Stokes solver, and the semi-span wing models were tested in a dry-air wind tunnel. The goal of this work was to acquire experimental data for code development, calibration, and validation. Measured and computed values for chordwise pressure distributions and spanwise load distributions agreed well for the iced and uniced swept wings at both 4° and 8° angle of attack. At 8° angle of attack, computations showed that the flow over the iced wing was massively separated. For the unswept wing at 8° angle of attack (but not for the swept wing), it was necessary to include tunnel wall boundary conditions at the wing root in order to get agreement between code prediction and experiment. These results suggested that wall suction should be incorporated into the tunnel to remove the boundary layer at the wing root. The ability to calculate surface streamlines and time averaged streamlines in massively separated flows offers a rich source of flow phenomena for comparison with experiments. Future plans for both the computational and experimental efforts were discussed.

Paper 8. - KIND and LAWRYSYN conducted a study of the effects of frost on airfoil aerodynamics. They acquired samples of real frost on plates left outside overnight and replicated the frost by a little-known technique that involves pouring dissolved liquid plastic over the frost. The plates with the plastic replicas of frost were used as the floor of a wind tunnel, and the boundary layer profiles were measured on these roughened plates. These profiles were inserted into the law of the wall to determine the ( $\Delta u/u^*$ ) shift. This velocity profile was used in a rough-wall integral boundary layer code to predict boundary layer growth over a wing covered with

frost. The boundary layer code coupled with an inviscid vortex panel code was used to calculate lift and profile drag for two airfoils, up to and beyond stall. A lifting line analysis was used with the airfoil results to determine wing aerodynamics as well as takeoff performance of two hypothetical aircraft with various amounts of frost coverage on their wing upper surface.

Hoar frost having a height of only 0.4 mm degraded wing performance and necessitated increased takeoff distances for both a small light aircraft and a large transport aircraft. Serious performance loss was predicted, however, only when the upstream edge of the hoar frost coverage was at, or very close to the suction peak in the pressure distribution. The dramatic lift losses occurred when frost was present in the region of strong adverse pressure gradients, just downstream of the suction peak, or in the region where the roughness height was several times greater than the boundary layer momentum thickness. In these regions, roughness caused the boundary layer to grow rapidly, and in the presence of adverse pressure gradients, made it prone to separation. When the upstream edge of the hoar frost coverage was beyond the suction peak, at the quarter-chord or further downstream, the computed lift and drag performance was approximately the same as for the clean wing.

Paper 9. - FLEMMING, BOND, and BRITTON presented results from icing wind tunnel tests of a lightly instrumented two-bladed teetering tail rotor from an OH-58 helicopter and a heavily instrumented subscale articulated main rotor for another helicopter. The models were exposed to variations in temperature, liquid water content, and droplet diameter and were operated over ranges of advance ratio, shaft angle, tip Mach number, and weight coefficient to determine the effect of these parameters on ice accretion and on rotor performance in icing. Ice profile tracings and ice molds were obtained. The paper presented the sensitivity of the model rotors to the test parameters and compared the results to analytical predictions. Test data quality was excellent and changes in lift and torque were remarkably repeatable. Analytical predictions for ice accretion and rotor performance agreed with the trends observed in the test. The techniques employed were validated by the excellent results obtained. The data should prove useful for code and scaling research and development within the helicopter industry.

Paper 10. - GENT reviewed the icing research being conducted at the Royal Aerospace Establishment in the UK. A copy of GENT's paper was not available for the meeting, but the technical evaluator later received from GENT a copy of the text he prepared for his talk. RAE's icing work was established to provide an understanding of the helicopter rotor icing problem, to provide engineers with tools needed to predict the effects of icing on rotor performance, and to develop the necessary rotor ice protection systems. The RAE have developed and combined a series of two-dimensional computer codes for predicting ice accretion on rotor blades: these include a potential flow code, a water droplet trajectory code, and a thermal heat balance code. The name of the ice accretion code is TRAJICE. They have also developed one-dimensional and two-dimensional codes for analyzing the performance of electrothermal ice protection systems for rotors. This includes analyzing the heat flow and temperature distribution inside the blades, the melting and freezing of ice on the rotors, and an elementary model for

ice shedding. They have combined the above codes with a rotor performance code that predicts torque and lift changes caused by icing. Calculated results from the ice accretion, electrothermal heater, and rotor performance in icing codes have been compared with and calibrated against available experimental data from icing tunnel and flight tests. The codes have been distributed widely to the aircraft industries in the UK, and special test cases have been compared with predictions from comparable codes developed by NASA and ONERA.

Paper 11. WICKENS and NGUYEN reported on a wind tunnel investigation into the effects of distributed upper surface roughness and leading edge ice formations on the performance of a powered wing model. This interesting paper began by citing a 1936 reference by Jones and Williams which showed that the loss in maximum lift was critically dependent on Reynolds number and also on roughness particle size. Jones and Williams found that at a Reynolds number of 10 million (typical for takeoff) loss in maximum lift approached 50 percent of clean airfoil values, while at the lower Reynolds numbers typical of low speed wind tunnel testing the loss in maximum lift was much lower. For the present paper, testing was done at a Reynolds number of 1.3 million for the clean wing and three different grit sizes, and at 2.3 million for the airfoil covered with heavy grade commercial sandpaper. Unfortunately, there was no data in which Reynolds number was varied while grit size remained constant, so any speculation as to the effects of Reynolds number in the present study has to be taken with caution. Aside from the above caveat, this paper contained unique data on powered-wing performance degradation caused by distributed upper surface roughness and leading edge ice.

Roughness height used on the model scaled to 1 to 3 mm for a 10-ft chord airfoil, which height was greater than normal frost buildup. In the unpowered state, roughness reduced the lift slope and maximum lift by 30 to 50 percent. The leading edge region was especially sensitive to these disturbances, and it was found that removing roughness from the first 15 percent of chord restored the wing to close to its original performance. Wing drag also increased as a result of surface roughness. Propeller power effects increased the lift slope and maximum lift above that of the clean wing; however, for the roughened wing, the lift coefficient for the powered wing dropped significantly below that for a clean, unpowered wing. It was concluded that the reduced lift slope and maximum lift caused by roughness would be very significant in event of engine failure at take off.

Leading edge ice accretion also caused large losses of lift and increases of form drag. However, a comparison between leading edge ice and upper surface roughness showed that leading edge ice produced a smaller reduction of lift slope prior to flow separation.

Increased drag was attributed partly to an increase in skin friction in unseparated flow, but mainly to increases in form drag after premature separation occurred. It was explained that if the roughness elements protrude above the laminar sublayer of the turbulent boundary layer in attached flow, the result is an increase in skin friction and the production of more turbulence. In suggesting an explanation for the higher losses in maximum lift at the higher Reynolds numbers, it was pointed out that increasing the Reynolds number would reduce the laminar

sublayer around the nose, thus aggravating the effect of roughness elements and increasing the probability of separation.

Paper 12. - LYNCH, VALAREZO, and McGHEE reported on experimental studies of the aerodynamic penalties caused by very thin leading edge ice formations (simulated by distributed roughness over that portion of the leading edge where ice would accumulate in flight). The geometries studied included single element configurations (airfoil and three-dimensional tail) as well as multi-element high-lift configurations. Emphasis was placed on obtaining results at high Reynolds numbers to insure the applicability to full-scale.

Even small ice thicknesses caused maximum lift losses of approximately 40 percent for single element airfoils. Losses in angle of attack margin to stall were also substantial—as high as 6°. Percentage losses for multi-element airfoils were not as severe as for single-element configurations, but degradations of the angle of attack margin to stall were the same for both. On jet transports, single-element airfoil results would apply to horizontal tailplanes, and multi-element results to wings.

The results for single-element airfoils with leading-edge roughness were found to correspond roughly to Brumby's correlation for the entire upper surface roughened and slats retracted (left hand curve on Fig. 1). This finding contradicts the previously held assumption that Brumby's more liberal correlation (that is, for roughness restricted to only the leading edge, and given by the right hand curves on Fig. 1) could be used to assess the effect of in-flight ice accretions.

This paper contains important new information about the effects of Reynolds number on the loss in maximum lift for modern, single-element airfoils with distributed roughness over that portion of the leading edge where in-flight icing would accumulate. They showed that losses in maximum lift increased rapidly over a chord Reynolds number range from  $2.5$  to  $5.0 \times 10^6$ , and beyond that the losses became nearly independent of Reynolds number. Maximum lift losses increased with increased roughness height-to-chord ratios.

The paper also obtained a simple linear correlation for loss in angle of attack margin to stall versus log of roughness height-to-chord ratio (Fig. 2). The results apply to both single- and multi-element airfoils and are independent of Reynolds number in the range of 5 to  $16 \times 10^6$ . The correlation provides a quick way to assess the maximum lift penalties incurred for a leading-edge ice roughness buildup on any representative wing or tail configuration. Simply use the lift versus angle of attack curve for the clean configuration and reduce its stall angle by the amount given by Fig. 2. It also provides the information needed to check on the adequacy of stall warning systems when anti-icing protection is not provided.

Since modern high bypass engines have minimal engine bleed air, airframers have effectively lost their supply of hot air for thermal anti-icing ice protection systems. Therefore they have been keenly interested in the promising new impulse deicing systems that do not require bleed air for operation. These new impulse deicers can prevent ice thicknesses from exceeding about 0.030 in.,



which is far better than the older pneumatic deicers could do. But unfortunately, the important message from this paper is that even thicknesses as small as 0.030 in. could cause maximum lift losses of approximately 40 percent for single element airfoils. The results presented in this paper indicated that even 0.005 in. ice roughness may cause unacceptable aeropenalties. With the airframers hard-pressed to find any other alternative to compressor bleed air, the finding that the new impulse systems may cause unacceptable aeropenalties will likely create controversy among those responsible for ice protection on modern jet transports. It is expected that this paper should stimulate a more intense investigation of the effects of roughness on the aeroperformance of future transports.

**Paper 13.** - BOER showed how upper surface wing roughness (representative of ground frost, snow, and ice) degraded the Fokker 50 aircraft aerodynamics and lead to reduced flight safety during takeoff. Results were reviewed for (1) tests conducted in Sweden's FFA wind tunnel in the early 1970's on multi-element airfoils with differing levels and degrees of roughness; (2) poweroff wind tunnel tests on a complete model of the F27 (scale 1:20) with upper surface roughness (which scaled to about 2 mm at full-scale); and (3) a fixed-base engineering flight simulator study of the F50's performance and flight handling characteristics during takeoff with wing upper surface roughness.

The wind tunnel studies of multi-element airfoils showed severe losses in maximum lift and large reductions in stall angle of attack. Roughness, representative of hoar frost, increased the boundary layer over the upper surface and de-cambered the wing, thus causing loss of lift and increase in drag for a given angle of attack. The tests clearly demonstrated that there was no difference in aerodynamic degradation due to hoar frost between slatted and nonslatted configurations. (Note that this could appear to differ from the results given in paper 2, but Fig. 1 shows that if the roughness is thick enough, use of extended slats does not recover the losses.)

For the F50 or F27 with a clean wing, a combined leading and trailing edge type of stall starts in the vicinity of the engine nacelle and progresses gradually inboard and outboard. This clean-wing stall was designed to allow the pilot to retain lateral control for as long as possible and to have favorable pitching moment characteristics throughout the stall. The wind tunnel tests of the F27 scale model showed that a roughened wing caused a pure trailing edge type of stall to occur simultaneously over the entire wing span. The roughness therefore seriously jeopardized the safety features designed into the clean-wing stall. Roughness coverage of 100 percent considerably deteriorated the aerodynamic characteristics of the Fokker 50, and furthermore, tests showed that cleaning the leading edge up to 15 percent wing chord did not restore the clean wing lift and drag characteristics. This last finding appears to disagree with the findings in papers 8 and 11.

The results of the Fokker wind tunnel tests were introduced into the aerodynamic data base of the F50 in the Fokker Aircraft fixed-base engineering flight simulator. Performance and flight handling characteristics during takeoff with contaminated wings were evaluated by a pilot. From these simulator studies it was concluded that wing contamination seriously deteriorated aircraft behavior in

takeoff. The pitch response to elevator input was slow. Extreme stickforces were required for rotation, and this would probably compel the pilot to abort the takeoff. After liftoff the aircraft was mistrimmed, which required very large pull forces. A large increase in takeoff distance was required. No improvement was found from cleaning the wing leading edge only or by increasing rotation speed. The results clearly demonstrated the importance of Advisory Circular AC 20-117 emphasizing the 'clean aircraft concept' under adverse weather conditions before takeoff.

This is one of the few papers published on the simulator results of upper wing surface roughness. It is hoped that in the future the entire icing scenario—takeoff, climb, cruise, hold, approach, and landing—will routinely be modeled in engineering simulators.

**Paper 14.** - WELTE, WOHLRATH, SEUBERT, DeBARTOLOMEO and TOOGOOD presented a detailed account of the various analyses and tests they carried out as part of the process to qualify the Dornier 328 to the FAR/JAR 25 requirements for operation in known icing conditions. This paper could be recommended for anyone who wants to understand the various steps that must be carried out before going into flight testing in natural icing. The first part of the paper discusses ice protection systems for the airframe, and the second part for the engine.

All lifting surfaces were pneumatically deiced, as were all the protected surfaces in the engine intake. Appropriate two-dimensional or three-dimensional CFD codes were used to calculate cloud droplet impingement limits over a wide range of operating conditions. In the engine intake tests, even the three-dimensional flow in the engine test cell connecting pipes was modeled in order to define test conditions that were most representative of critical icing conditions. Theoretical calculations were done for take-off, climb, hold, descent, approach, and landing conditions using adequate center of gravity locations, flap settings, elevator and rudder deflections.

To get early information about the aerodynamic degradation due to ice accretion, many tests were performed in the DNW wind tunnel (The Netherlands) on a 1:4.2 scaled model of the complete aircraft with artificial ice shapes on the leading edge of lifting surfaces. Separate tests of the empennage were performed to guarantee safe operation in heavy ice. These data were the basis for increased landing speeds and limitations to flap settings in icing conditions.

Elevator horn icing was modeled with a two-dimensional ice accretion code, and the 1:4.4 scaled horn was tested in an icing wind tunnel. Icing scaling laws were used to determine the icing tunnel test matrix.

Mr. TOOGOOD noted that in testing the engine air intake the most critical conditions occurred between -5 and 0 °C, even though the FAA does not require testing above -5 °C. The higher LWC's associated with the warmer temperatures leads to water runback and freezing beyond the protected areas. He felt that these results, which he has seen in other engine test programs as well, were important enough to recommend that the FAA change their certification procedure to include testing from -5 to 0 °C.

Paper 15. - DUNHAM, DUNHAM, and BEZOS summarized the NASA research on effects of heavy rain on airfoils. The paper was presented by Dr. E. WAGGONER from NASA Langley. Covered in this paper were background of work done to date on heavy rain effects, measurements of natural rain rates, wind tunnel heavy rain tests on single- and multi-element airfoils with chord Reynolds numbers from  $1.8$  to  $3.3 \times 10^6$ , large scale track testing with chord Reynolds numbers from  $11$  to  $18 \times 10^6$ , and scaling considerations.

Heavy rainfall rates are being acquired for short sample times at 6 geographical sites. Over 7000 rainfalls with rates above  $100$  mm/hr have been measured since 1988. The maximum rate measured was  $720$  mm/hr for just under  $10$  sec. One quarter percent of the events exceeded  $500$  mm/hr for events up to  $10$  sec.

Both subscale and full-scale tests showed that extremely heavy rain of  $900$  mm/hr produced a reduction in maximum achievable lift coefficient of at least  $15$  to  $20$  percent, and a reduction in angle of attack to stall margin of  $4^\circ$  to  $8^\circ$ . The high-lift configurations (i.e., leading- and trailing-edge devices deployed) were more sensitive to heavy rain than was the cruise configuration. WAGGONER suggested, after the talk, that in the heavy-lift configuration the slat gap seems to become blocked with water, but he also said that this conference made him aware of the strong effect of surface roughness on maximum lift loss.

WAGGONER suggested that a better understanding of the physics of heavy rain effects is needed before analytical techniques will be able to successfully model the phenomena. Test results did not show a strong Reynolds number scaling effect, and it was therefore concluded that low speed wind tunnel test techniques are valid for obtaining first-order effects of heavy rain. (This conclusion was not supported by the test results presented in paper 17, but as will be discussed below, there is some question about the interpretation of those test results.)

Based on the test results, DUNHAM, et al. concluded that since transport aircraft normally avoid high angle of attack maneuvers, their normal operations should not be affected by heavy rain. However, should heavy rain occur during a severe low-altitude wind shear, the pilot procedures used to counter the wind shear effects may result in operating at a higher than normal angle of attack. In a comment from the audience, it was urged that the required research on heavy rain be carried out before considering any changes to the pilot procedures for wind shear.

Paper 16. - FEO, ROGLES, and URDIALES presented a paper on measurement of water film thickness on airfoils in heavy rain conditions using conductance sensors. They compared the performance of one, two, and three electrode sensors and showed that the triple electrode sensor is superior to the others in accuracy and continues to hold its accuracy even when electrolytic corrosion contaminates the probe. The triple electrode sensors also accurately measure thicknesses of wavy surface films. After an appropriate calibration method is established, triple electrode sensors are valid for any liquid type and condition. Therefore, these sensors are suitable for heavy

rain applications. The mean error obtained in the calibrations was  $\pm 0.025$  mm for measurements in the  $0$  to  $0.5$  mm range.

Paper 17. - TANG also presented wind tunnel test results for heavy rainfall on a two-dimensional multi-element, high lift airfoil. Effective rainfall rates ranged from  $50$  to  $300$  mm/hr, and chord Reynolds numbers ranged from  $1.7$  to  $8.8 \times 10^6$ . The measured loss in maximum lift ranged from  $6$  to  $16$  percent, and drag levels at constant lift were up to  $43$  percent higher under wet conditions.

The tests were conducted in a blowdown wind tunnel, in which a run consisted of continuously changing the angle of attack from negative values up to and beyond stall, all at a constant water flow rate through the nozzles. Apparently because of a water flow rate limit through the nozzles, the rain rate was reduced as the Reynolds number was increased. Thus, there were no sets of data where the rain rate was held constant while the Reynolds number was varied, or vice versa. To isolate the effect of Reynolds number, TANG assumed that the rain effects on lift increment depended linearly on rain rate. So he normalized all the lift increment data to  $50$  mm/hr by multiplying the lift increment by  $50$  and dividing it by the actual rainfall rate. There seems to be no justification for this normalization procedure, but after it was done, the lift loss versus angle of attack showed a strong Reynolds number effect. In contrast, the authors of paper 15 did not find a strong Reynolds number effect. To resolve this difference, it would be very desirable to conduct a series of tests with rain rate held constant for all runs while changing only the Reynolds number from one run to the next.

Another potential test problem involves the procedure of continuously changing the pitch during a run. In a private discussion with WAGGONER, who presented paper 15, he pointed out that NASA found that it took about  $1.5$  to  $2$  sec for the lift to settle down after the angle of attack was changed. So it should prove beneficial if this test could be rerun using a stepping motor that would pitch the model and pause for fixed times before going on to the next angle.

Paper 18. - Papers 18 and 19 discuss the aerodynamic effects of aircraft ground deicing/anti-icing fluids. The authors of these two papers collaborated on some key aspects of this fluids work. So while the same information may have appeared in both papers, it will be included in only one or the other of the discussions of these two papers. CARBONARO presented a historical review of the research carried out by the von Karman Institute (VKI) on the flowoff properties and aerodynamic effects at takeoff of these fluids. He also described the rationale and a test methodology for an aerodynamic acceptance criteria for these fluids.

In general, anti-icing fluids are non-Newtonian, while deicing fluids are Newtonian. The viscosity of anti-icing fluids varies inversely with shear stress, while that of deicing fluids is independent of shear stress. The non-Newtonian anti-icing fluids tend to form on the surface of the wing a protective fluid layer, which does not flow off the wing while the airplane is grounded and which prevents ice from adhering to the wing during long waits in freezing precipitation before takeoff. During takeoff, airflow over

the wing subjects the fluid to a large shear stress, and in the ideal case, the fluid should flow off the wing, leaving it clean at the moment of rotation.

The use of non-Newtonian anti-icing fluids was widespread in Europe when Boeing Airplanes published a report in which they warned that some fluid remained on the wing at takeoff and could degrade takeoff performance sufficiently to require takeoff adjustments for some aircraft. The Boeing report triggered a reaction of several European Airlines, and in 1983 the VKI was requested to further study the problem. Boeing's findings were confirmed by researchers at VKI on a large-scale wing in a refrigerated wind tunnel. At VKI, they also determined that the final fluid film thickness on the wing at rotation was independent of the initial application thickness. This finding allowed them to eliminate the original film thickness as an important variable.

At VKI they determined that maximum lift loss could not be correlated with fluid viscosity alone, as a fluid of high viscosity could yield lower losses than another fluid with lower viscosity. This was important because it meant that quality control of the deicing/anti-icing fluids could not be made by a viscosity check, but that an aerodynamic test was required—at least until the mechanism of fluid flowoff and lift loss is fully understood and modeled. At VKI they analytically studied the aerodynamics of wings with surface contamination by combining a nonviscous panel flow code with a boundary layer analysis for rough or wavy surfaces. These studies suggested that it might be possible to correlate maximum lift loss with the air boundary layer displacement thickness at the wing trailing edge. Further wind tunnel tests by both VKI and Boeing confirmed that maximum lift loss correlated with trailing edge displacement thickness.

While Boeing undertook a comprehensive wind tunnel test of these fluids on a two-dimensional section model and a three-dimensional half model of the Boeing 737-200 ADV airplane at the NASA Lewis Research Center, VKI researchers measured the boundary layer displacement over a flat plate covered with fluid in a wind tunnel where the velocity was ramped to reproduce takeoff speeds. (The floor of the tunnel served as the flat plate.) VKI found that for a given fluid and a given air temperature the maximum lift loss measured for wings correlated with the boundary layer displacement thickness at the trailing edge of the flat plate. Boeing found that this correlation also held for the Boeing two-dimensional wing data and airplane half model data.

VKI then developed a simple methodology to measure displacement thickness at the trailing edge of a flat plate. They applied the fluid on the test section floor of a small, refrigerated wind tunnel, and ramped the speed through a prescribed takeoff run. They obtained the boundary layer displacement thickness by measuring the increase in airspeed between entrance and exit of the test section, which was a measure of the tunnel blockage caused by the boundary layer. (CARBONARO cautioned that the wind tunnel dimensions must be measured very accurately, or the derived boundary layer displacement thicknesses will contain large errors.) New fluids submitted for ground deicing/anti-icing applications are now conveniently tested in small wind tunnels to determine their effect on flat plate boundary layer displacement thickness. Those fluids that produce boundary layer displacement thicknesses below

predetermined limiting values are judged aerodynamically acceptable. These predetermined values are based on aerodynamic considerations that are discussed in paper 18.

Paper 18. - ZIERTEN and HILL reported on a comprehensive follow-on wind tunnel investigation of aircraft ground deicing/anti-icing fluids that was performed to supplement earlier reported flight and wind tunnel tests and to support the development of aerodynamic acceptance criteria for aircraft ground deicing/anti-icing fluids. The test was conducted at the NASA Lewis Icing Research Tunnel using both a two-dimensional wing model and a three-dimensional half model of the Boeing 737-200ADV airplane. The fluids tested included three Type I Newtonian fluids, which use ethylene, diethylene, and propylene glycol as the freezing point depressant; four Type II non-Newtonian fluids, which are currently in production; eight developmental fluids; and a Mil Spec fluid to be used as a reference fluid in the aerodynamic acceptance test. The Type I and current Type II fluids were tested neat and diluted with water to determine basic aerodynamic effects. Diluting the Type II fluids did not significantly alter the aerodynamic effects of the fluids. Diluting the Type I fluids to the dilutions used in practice significantly reduced the adverse aerodynamic effects of these fluids, especially at temperatures of -10 °C and colder. Air boundary layer displacement thickness measurements made with the fluids on the two-dimensional model showed excellent correlation with lift loss due to the fluids at maximum lift and at operating angles of attack and with the boundary layer displacement thickness measured on a flat plate in a small VKI wind tunnel. This correlation validated the future use of flat plate boundary layer displacement thickness measurement as the criterion for the aerodynamic acceptability of a fluid. The limiting boundary layer displacement thickness, which identifies a fluid as being aerodynamically acceptable, was correlated with a 5.24 percent loss in maximum lift that results in an allowed specific reduction in aerodynamic performance margins at takeoff.

## DISCUSSION AND EVALUATION

A discussion of the individual papers was included in section 2.0. This section will discuss major subject areas in a broader context.

### Certification for Flight into Known Icing Conditions

Papers dealing with aircraft icing certification revealed that CFD computer codes are used routinely in the certification process to predict droplet trajectories, droplet collection efficiencies, and ice accretion shapes. Codes are used to design ice protection systems, to locate icing instruments on aircraft, and to provide the geometry of artificial ice shapes for use on airplanes in clear air testing. While two-dimensional ice accretion codes are in common use, three-dimensional codes are just becoming available for swept airfoils (Ref. 7), and there are not yet any general three-dimensional ice accretion codes available. These are beginning to be developed, and their development is highly recommended.

While several papers provided analytical methodologies to predict aero penalties due to roughness, there was no indication that these methods were sufficiently validated to be accepted as part of the

certification process. Development, calibration, and validation of codes that predict aeroperformance of iced airfoils is highly recommended.

The FAR/JAR 25 regulations are reasonably specific in their requirements for demonstrating compliance of aircraft ice protection systems, and procedures are well established for correlating ice protection test results from icing wind tunnels, icing flight testing, and analysis. But the French certification authorities feel that the regulations are not sufficiently explicit to demonstrate the effects of ice accretions on aircraft performance and flight handling qualities. Their response has been to develop a Joint Advisory Material AMJ-25-1419 that calls for explicit flight tests with artificial ice in clear air for cases of (1) engine failure during take-off into known icing conditions, (2) cruise, holding, and landing with ice on unprotected parts of the aircraft and with ice accumulated between cycles on parts protected by deicing systems, and (3) ice accumulations that occur when ice protection systems fail in flight, (4) and a specific form of ice that, with a small thickness and the abrasiveness of sandpaper, has been used to qualify the behavior of aircraft during pushover maneuvers. This testing would be backed up with flights in natural icing conditions. The AMJ also proposed that when the ice protection system is turned on, the stall warning system should be reset to values appropriate to the lower stall angle, and stall speeds be adjusted to the maximum lift observed in the icing flight trials with artificial ice shapes.

The Advisory AMJ-25-1419 appears to make good sense, and since it incorporates material already being used in Canada and possibly elsewhere, it deserves to be carefully considered by certification authorities everywhere.

As was noted above, airplanes operate with portions of their lifting surfaces unprotected from in-flight icing, so they will fly and land with some surface contamination. Deicing systems allow ice to accumulate between deicer actuations and usually leave some residual ice after actuation. Thus, an aircraft equipped with deicers will fly and land with some ice contamination. Even during climbout it is possible to accumulate ice if the ice protection systems must remain inoperable until a prescribed height is reached. An airplane will also accumulate ice if the ice protection system fails during flight.

While some of the papers gave guidance as to the losses in maximum lift allowed during takeoff, little guidance was offered for losses in maximum lift allowed during approach and landing. This issue is more complex because landing speeds and landing wing configurations are dictated not only by safety considerations but also by other customer requirements. Aircraft operators want minimum field lengths for landing, thus they don't want residual ice from in-flight icing encounters to cause large increases in landing stall speeds. Also, since in-flight icing usually occurs in winter conditions that are likely to be accompanied by slippery runways, the operators want to avoid increases in stall speeds so as to prevent landing mishaps. And finally, aircraft operators want low noise levels to ensure that they can operate out of airports with strict noise abatement policies. So, although lift can also be regained by using more flap, that would increase drag and require high engine power settings, which in turn would increase engine noise.

In paper 12 it was shown that as little as 0.005 in. thick roughness on unsaltered airfoils caused 20 percent maximum lift losses. As also noted in paper 12, if in-flight ice causes lift decreases of 20 percent, then wing area must increase by 20 percent to compensate. Jet transports have traditionally prevented any ice formation on their unsaltered tailplanes by employing hot bleed air anti-icing systems to evaporate impinging cloud water. But the loss of bleed air on high bypass engines is forcing airframers to consider replacing anti-icing systems with deicing systems. Even the new impulse deicing systems build up much more than 0.005 in. of ice thickness between deicer activations, and most have more than 0.005 in. thick residual ice after actuation. Thus the study of paper 12 is important because it shows that it would be extremely difficult to utilize a deicing system without paying the penalties associated with increased tail area. But competition is forcing airframers to use minimum wing and tail area to achieve the greatest range and lowest fuel consumption. Thus the airframers will be forced to conduct numerous tradeoff studies before they can say for certain what the best solution is for future in-flight ice protection. They may be forced to use auxiliary power units or special air heaters to provide for anti-icing air. It is hoped that the results of these trade studies can be made available to the ice protection industry so that they can properly direct future ice protection technology development.

#### The Effect of Surface Roughness on Wing Aerodynamics

Several papers in this meeting contained important new experimental data and/or modified analytical methods for determining the effects of surface contamination on the aerodynamic performance of single-element and multi-element airfoils and of the overall aircraft. The findings that surface roughness seriously degrades airplane takeoff performance and handling qualities acutely reinforces the FAA's requirement that the wings must be clean at takeoff.

As noted in the Introduction, the literature on surface roughness is extensive. Yet, progress has been very limited in developing analytical models and computer programs for predicting the aerodynamics of roughened surfaces. Some perceive the challenge of the roughness problem as comparable to that of turbulence. Indeed, in the viscous analyses of surface roughness, turbulence models are important. It is also expensive and time consuming to acquire a systematic set of experimental data for the wide range of surface contaminations created by nature and for the wide range of airfoils used by the airframers.

New experimental data (paper 12) on roughened, modern airfoils revealed the importance of testing at full-scale wing chord Reynolds numbers: losses in maximum lift increased with Reynolds numbers in the range of 2.5 to  $5 \times 10^6$  and then held constant for higher values. Unfortunately, most airfoil data is obtained below  $5.0 \times 10^6$  in low speed wind tunnels; it requires either a very large wind tunnel or a pressurized tunnel to test at the higher Reynolds numbers. Obviously, testing at the lower Reynolds numbers gives an indication of the roughness effects, but apparently it will not give good absolute numbers needed by aircraft designers. There is also the other question as to whether the physics of roughness, as applied to full-scale wings, can be determined from fundamental studies conducted at the lower Reynolds numbers.

Although maximum lift losses for wings contaminated with grit were shown to be sensitive to Reynolds number, there is still no knowledge as to whether wings with leading edge ice shapes would exhibit a similar Reynolds number sensitivity. Ice, for example, causes a continuum of leading edge surface distortions: during light icing conditions, surface roughness; during rime icing conditions, aerodynamically shaped ice growths on the leading edge (but the ice is rough); and during glaze ice conditions, large, bulbous, rough leading edge shapes. The variety of possible ice shapes was illustrated in paper 10. Navier-Stokes solutions (paper 7) on a leading edge glaze ice shape showed the ice caused a leading edge flow separation bubble. It is possible that this leading edge stall caused by glaze ice might be relatively insensitive to Reynolds number. This possibility seems to add more complexity to the problem; that is, the various kinds of leading edge distortion must each be examined for Reynolds number effects to determine how best to model and test each kind of icing.

As was recommended in the meeting, a systematic study of Reynolds number effects on airfoil performance degradation due to ground and in-flight ice contamination is needed to support development of both empirical and analytical models.

Professor Slooff suggested at the meeting that we should look at the large body of work done on surface roughness by naval hydrodynamicists, and he later provided Ref. 8 on the subject.

#### Heavy Rain Effects

It has been clearly demonstrated in wind tunnel and track testing that heavy rain significantly reduces both maximum lift and stall angle. Yet, because of the difficulty and expense in conducting heavy rain tests, the database is rather limited. Again, because of the difficult experimental conditions, knowledge of the physics of the aerodynamic effects of heavy rain is also rather limited.

While NASA Langley found that low Reynolds number wind tunnel testing yielded effects that were a good first order approximation to full-scale, the Canadian National Research Council (NRC) found a strong sensitivity to Reynolds number. But during testing, the NRC never held rain rate constant while varying only Reynolds number. Unfortunately, their assumption that lift loss increments depended linearly on rain rate was not substantiated, so it is important to repeat the wind tunnel test using the same rain rate for several different Reynolds numbers.

Under normal low angle of attack operation, heavy rain would not present a safety hazard; but if heavy rain accompanied low-altitude windshear, it could present an additional safety hazard because pilot procedures require high angles of attack in such situations. Further research should be done on heavy rain effects before recommending that current pilot procedures for operations in windshear be modified.

#### Ground Deicing/Anti-icing Fluids

It appears that the effects of ground deicing/anti-icing fluids on takeoff performance are sufficiently well understood, from an empirical approach, for application to

the large jet transports. Fluid specification and aerodynamic acceptance criteria have been worked out and are acceptable to members of the Aerospace Industries Association (AIA), which represents the manufacturers and users of the jet transports in both Europe and North America. The AIA's criteria for acceptable loss in maximum lift was based on allowing the 737-200ADV's 13 percent stall speed margin for clean wing takeoffs to drop to 10 percent margin when taking off with fluid contamination on the wings. The 10 percent stall margin is the minimum allowed by FAA regulations. Using the relationship that stall speed is inversely proportional to the square root of maximum lift, the above criteria for an allowable loss in stall margin translates into a 5.24 percent allowable loss in maximum lift. This appears not to be a problem for most transport aircraft, although for some an adjustment in take-off procedure would be necessary.

During the meeting, questions were raised as to whether in the wind tunnel testing the time-to-rotation should have been reduced in proportion to the scale reduction of the wind tunnel model chord. But because the increments in lift loss and stall angle reduction were consistent with those increments found in flight testing, the authors believed the tunnel testing approach was appropriate.

Given the complexity of the phenomena in fluid flowoff, such as the wave development due to shear stress on a non-Newtonian fluid and the accompanying thickening of the air boundary layer and decambering effects, it is remarkable that such an easy empirical aerodynamic acceptance criteria was found. In the longer term, however, more effort should be devoted to understanding the mechanisms of fluid flowoff and lift loss for these fluids. In particular, not only fluid viscosity but also fluid elasticity (Ref. 9) should be considered in any analytical or numerical model that describes the surface film wave development and flowoff behavior of these fluids. The effects of fluid-to-air viscosity ratio on liquid film wave growth were studied in Ref. 10. Ultimately, it would be desirable to develop an acceptance criteria that depended on specifying only the physical and chemical properties of the fluid, as is done for Mil Spec fluids. Unfortunately, current formulations of non-Newtonian fluids are highly proprietary.

Although nothing was mentioned about the effect of these fluids on aircraft with takeoff speeds below 85 knots, such as the commuter and general aviation categories, it is known that these fluids may seriously degrade take-off performance of some of these aircraft. Limited flight testing of these fluids on general aviation aircraft has led to the recommendation that they not be used for general aviation (Ref. 11). When used on commuters, adjustments in take-off procedures will be necessary for some aircraft. Such adjustments include holding the aircraft on the ground up to 30 sec during the takeoff run to enhance fluid runoff, and increasing takeoff speeds to compensate for the increased stall speeds caused by the degradation in maximum lift (Ref. 12). Some fluid manufacturers offer a "Type 1-1/2" fluid that has shorter holdover times in freezing precipitation, but also causes smaller aerodynamic penalties for smaller aircraft (Ref. 13).

The manufacturers and users of commuter aircraft appear to be about three years behind the jet transports in evaluating the effects of these fluids on take-off

performance. But lest the wrong impression be given here, it should be noted that some aircraft manufacturers, such as deHavilland (Ref. 12) and Fokker (Ref. 14), have conducted extensive flight and/or wind tunnel testing of these fluids for selected aircraft and have issued winter advisories, and some users have been testing these fluids on aircraft in their fleets. And the Federal Aviation Administration (FAA) has been funding flight studies on the effects of these fluids on general aviation aircraft (Ref. 11).

## CONCLUSIONS AND RECOMMENDATIONS

The selection of papers in this meeting gave a balanced overview of the state-of-the-art with respect to prediction, simulation, and measurement of the effects of icing, anti-icing fluids, and precipitation (snow, frost, and heavy rain) on the aerodynamic characteristics of flight vehicles.

The current regulations FAR/JAR 25, for certification of aircraft for flight into known icing conditions, offers clear guidance on the certification of ice protection equipment, but appears not to be as specific on the flight test procedures for determining the safety hazards of leading edge ice on the aircraft's performance and handling qualities. The French Certification Authority's proposed regulatory changes, as embodied in Advisory Material Joint AMJ 25-1419, offers more specific procedures for evaluating the safety hazards of in-flight ice and is recommended for serious consideration by other certifying authorities.

The use of CFD codes for predicting droplet trajectories and limits of impingement, ice shapes, and ice protection system performance is widespread, and further refinement of the codes along with experimental calibration and validation is recommended. In particular the development of a general three-dimensional ice accretion code is recommended. Also recommended is the development of flow codes that predict changes in aeroperformance caused by ice accretion and other surface roughness. Ultimately, these codes should be combined into an overall airplane code that can predict ice formations and performance and handling qualities of a complete aircraft in an icing encounter.

More wind tunnel tests of complete aircraft models with simulated ice shapes and roughness is recommended. And inclusion of these wind tunnel data into fixed base

engineering simulators to determine performance and handling qualities under icing conditions is recommended. The wind tunnel data can also serve as calibration data for codes that predict overall aircraft performance and handling in icing.

A systematic experimental study of the effect of Reynolds number on surface roughness effects is strongly recommended. Such a study should consider not only surface roughness, but also leading edge ice shapes ranging from thin grit roughness associated with light icing to rough rime ice shapes and the even rougher and more bulky glaze ice shapes.

The next generation of high bypass turbofan engines will provide little or no excess bleed air for thermal anti-icing ice protection systems. Therefore the icing community has been forced to consider efficient deicing systems as a possible alternative to the conventional thermal anti-icing used on jet transports. One paper in this meeting reported that a wind tunnel study showed that even the small ice thicknesses achieved by the promising state-of-the-art impulse-type deicing systems would cause losses in maximum lift of approximately 40 percent for single element airfoils. This finding will likely create controversy and confusion within the icing community as to the future of deicing systems for jet transports. It is recommended that further study of the tradeoffs of deicing versus anti-icing be carried out by the manufacturers of jet transports and that the results be made available to the ice protection industry so they can properly direct future ice protection technology development.

Further studies of the effects of Reynolds number on heavy rain effects are recommended. Further study of heavy rain effects is recommended in order to justify incorporating heavy rain considerations into the pilot procedures that have been developed for coping with low-altitude windshear.

The development of an empirical aerodynamic acceptance procedure for ground deicing/anti-icing fluids was a remarkable achievement. Follow-on work should include development of an analytical model of the flowoff and aerodynamics caused by these fluids during takeoff. Ultimately, it would be desirable to develop an acceptance criteria that depended on specifying only the physical and chemical properties of the fluid, as is done for Mil Spec fluids.

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13. Salvador, R.: Application and Specification of De-/Anti-Icing Fluids for Aircraft with Different Short Takeoff Time and Rotation Speed. AIAA Paper 91-0560, Jan. 1991.
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Reynolds no.	Type of roughness	Reference
● $26 \times 10^5$	Sand grain band	"Theory of wing sections" (Abbot)
□ $31 \times 10^5$	Protruding strip	NACA TR446
◆ $31 \times 10^5$	Multiple grooves	NACA TN457
▲ $31 \times 10^5$	Carborundum grit	NACA TN457
△ $5 \times 10^5$	Sand grains	"Aerodynamische profile" (Riegels)
▶ $6.3 \times 10^5$	Wire mesh on surface	NACA TM375
◀ $3.1 \times 10^5$	FWD facing step	NACA TN457
◇ $3.1 \times 10^5$	Protruding strip	NACA TR446
○ $3.1 \times 10^5$	Protruding strip	NACA TR446
◊ $3.1 \times 10^5$	Protruding strip	NACA TR446
▲ $3.6 \times 10^5$	Carborundum grit	NACA TN457
▼	Frost (in icing tunnel)	NACA TN2962
▲ $24 \times 10^5$	Insect contamination	Flight training incident (DC-9)
△ $4.5 \times 10^5$	Simulated tailplane ice	DC-9
▶ $5.5 \times 10^5$	Simulated tailplane ice	DC-10
▼ $7.8 \times 10^5$	Simulated deicer boot*	C-133
■ $7.0 \times 10^5$	Carborundum grit	R&M 1703
✱ $24 \times 10^5$	Chipped paint on LE*	DC-9
◆ $29 \times 10^5$	Ballotini	NPL AR1308
■ $24 \times 10^5$	Burred rivets on LE	DC-9
● $3.2 \times 10^5$	Simulated frost	FFA RPT AU-902
○ $1.8 \times 10^5$	Simulated wing ice	FFA RPT AU-995
—	Simulated ice roughness	ICAO BUL Oct 77
▲ $-24 \times 10^5$	Simulated frost	(P737) Boeing airliner, Oct 83 (frost 8)
▲	Simulated frost	(737) VKI lecture (frost 2)
▲	Simulated frost	(757) VKI lecture (frost 2)
▲	Simulated frost	(767) VKI lecture (frost 2)
●	DC-9 wind tunnel	Test LB-155AN

Note: 737 and 767 with mid slats

Solid symbols indicate distributed roughness

Open symbols indicate singular disturbance

Flagged symbols indicate swept wing data

\* indicates unpublished data

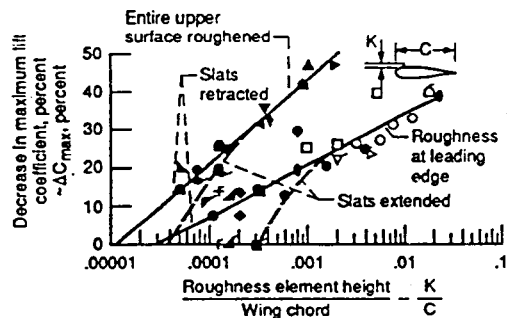


Figure 1.—Correlation of the effect of wing surface roughness on maximum lift coefficient. (From paper no. 2).

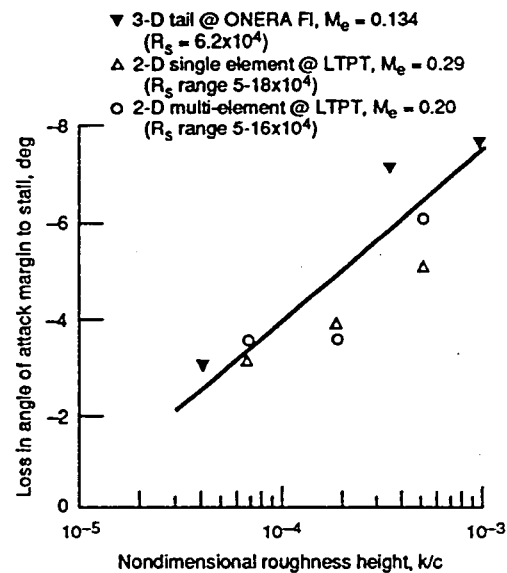


Figure 2.—Correlation of single-element and multi-element airfoil test results for loss in angle-of-attack margin to stall due to leading-edge roughness. (From paper no. 12).



# APPENDIX A

## LIST OF PAPERS - AGARD CONFERENCE PROCEEDINGS NO. 496

1. Flight In Adverse Environmental Conditions  
J. F. RENAUDIE, Formerly with STPAe, France -  
(INVITED)
2. The Effect of Wing Ice Contamination on Essential  
Flight Characteristics R.E. BRUMBY, Douglas  
Aircraft Co., USA
3. Low Temperature Environment Operations of Turbo-  
Engines  
R. JACQUES, Ecole Royale Militaire, Belgium -  
(INVITED)
4. Evolution of Regulation Addressed to Certification of  
Airplanes In Icing Conditions  
G. CATTANEO, CEV Istres, France - (INVITED)
5. Icing Simulation, a Survey of Computer Models and  
Experimental Facilities  
M.G. POTAPCZUK and J.J. REINMANN, NASA  
Lewis, USA - (INVITED)
6. Methods of Calculating the Collection Efficiencies of  
Water Droplets in Three Dimensions with Industrial  
Applications  
P. PREL, Aerospatiale, France
7. Simulation of Iced Wing Aerodynamics  
M.G. POTAPCZUK, NASA Lewis; M.B. BRAGG,  
Univ. of Ill.; and O.J.KWON and L.N. SANKAR,  
Georgia Institute of Technology, USA
8. Effects of Frost on Wing Aerodynamics and Take-Off  
Performance  
R.J. KIND, M.A. LAWRYSYN, Carleton Univ.,  
Ottawa, Canada
9. Model Rotor Icing Tests in the NASA Lewis Icing  
Research Tunnel  
R.J. FLEMMING, Sikorsky Aircraft Div. UTC; T.H.  
BOND, R.K. BRITTON, NASA Lewis, USA
10. A Review of Icing Research at the Royal Aerospace  
Establishment  
R.W. GENT, RAE, UK
11. Wind tunnel Investigation of a Wing-Propeller Model  
Performance Degradation due to Distributed Upper-  
Surface Roughness and Leading Edge Shape  
Modification  
R.H. WICKENS, V.D. NGUYEN, NRC, Canada
12. The Adverse Aerodynamic Impact of Very Small  
Leading-Edge Ice (Roughness) Buildups on Wings and  
Tails  
F.T. LYNCH and W.O. VALAREZO, Douglas  
Aircraft Co., and R.J. McGHEE, NASA Langley
13. The Effect of Hoar-Frosted Wings on the Fokker 50  
Take-off Characteristics  
J.N. BOER, Fokker Aircraft, Netherlands
14. Preparation of the Ice Certification of the Dornier 328  
Regional Airliner by Numerical Simulation and by  
Ground Tests  
D. WELTE, W. WOHLRATH, R. SEUBERT,  
Dornier Luftfahrt, Germany; W. Di BARTOLOMEO,  
R. TOOGOOD, Pratt & Whitney Canada Inc.,  
Canada
15. A Summary of NASA Research on Effects of Heavy  
Rain on Airfoils  
D.J. DUNHAM, R.E. DUNHAM, Jr., G.M. BEZOS,  
NASA Langley, USA
16. The Measurement of Water Film Thickness on Airfoils  
in Heavy Rain Conditions Using Conductance Sensors  
A. FEO, F. ROGLES, M. URDIALES, INTA, Spain
17. Experimental Investigation of Heavy Rainfall Effect  
on a 2-D High Lift Airfoil  
F.C. TANG, NRC, Canada
18. Aerodynamic Effects of De/Anti-Icing Fluids, and  
Description of a Facility and Test Technique for Their  
Assessment  
M. CARABONARO VKI, Belgium
19. Wind Tunnel Investigation of the Aerodynamic Effects  
of Aircraft Ground Deicing/Anti-Icing Fluids and  
Criteria for Aerodynamic Acceptance  
T.A. ZIERTEN, E.G. HILL, Boeing Co., USA

APPENDIX B  
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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1991	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE Technical Evaluation Report, AGARD Fluid Dynamics Panel Symposium on Effects of Adverse Weather on Aerodynamics		5. FUNDING NUMBERS  WU-505-68-10		
6. AUTHOR(S) J.J. Reinmann				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		8. PERFORMING ORGANIZATION REPORT NUMBER  E-6460		
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Washington, D.C. 20546-0001		10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA TM-105192		
11. SUPPLEMENTARY NOTES Responsible person, J.J. Reinmann, (216) 433-3900.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Categories 01 and 02			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  The Fluid Dynamics Panel of AGARD sponsored a Specialists Meeting on "Effects of Adverse Weather on Aerodynamics" on April 29 to May 1, 1991, in Toulouse, France. The purpose of the meeting was to provide an update of the state-of-the-art with respect to the prediction, simulation and measurement of the effects of icing, anti-icing fluids and various forms of precipitation on the aerodynamic characteristics of flight vehicles. Sessions were devoted to introductory and survey papers and icing certification issues, to analytical and experimental simulation of ice frost contamination and its effects on aerodynamics, and to the effects of heavy rain and deicing/anti-icing fluids. The 19 papers announced for the meeting are published in AGARD Conference Proceedings CP-496 and are listed in the Appendix of this report. A brief synopsis of each paper and some discussion, conclusions and recommendations are given in this evaluation report.				
14. SUBJECT TERMS Ice formation; Aerodynamic characteristics; Aircraft performance; Ice prevention; Cold weather tests			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	



National Aeronautics and  
Space Administration

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